Infrared Mass-to-Light Profile Throughout the Infall Region of the Coma Cluster

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ABSTRACT

Using a redshift survey of 1779 galaxies and photometry from the 2-Micron All-Sky Survey (2MASS) covering 200 square degrees, we calculate independent mass and light profiles for the infall region of the Coma cluster of galaxies. The redshift survey is complete to $K_s = 12.2$ (622 galaxies), 1.2 magnitudes fainter than $M^*_{K_s}$ at the distance of Coma. We confirm the mass profile obtained by Geller, Diaferio, & Kurtz. The enclosed mass-to-light ratio measured in the K_s band is approximately constant to a radius of 10 h^{-1}Mpc, where $M/L_{K_s} = 75 \pm 23 h M_\odot/L_\odot$, in agreement with weak lensing results on similar scales. Within $2.5h^{-1}$Mpc, X-ray estimates yield similar mass-to-light ratios ($67\pm32h$). The constant enclosed mass-to-light ratio with radius suggests that K-band light from bright galaxies in clusters traces the total mass on scales $\lesssim 10$ h^{-1}Mpc. Uncertainties in the mass profile imply that the mass-to-light ratio inside r_{200} may be as much as a factor of 2.5 larger than that outside r_{200}. These data demonstrate that K-band light is not positively biased with respect to the mass; we cannot rule out antibias. These results imply $\Omega_m = 0.17 \pm 0.05$. Estimates of possible variations in M/L_{K_s} with radius suggest that the density parameter is no smaller than $\Omega_m \approx 0.08$.

Subject headings: cosmology: observations — dark matter — galaxies: clusters: individual (Coma) — galaxies: kinematics and dynamics — galaxies: photometry

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1. Introduction

The relative distribution of matter and light in the universe is one of the outstanding problems in astrophysics. Clusters of galaxies, the largest gravitationally relaxed objects in the universe, are important probes of the distribution of mass and light. Zwicky (1933) first computed the mass-to-light ratio of the Coma cluster and found that dark matter dominates the cluster mass. Recent determinations yield mass-to-light ratios of $M/L_{B_j} \sim 250hM_\odot/L_\odot$ (Girardi et al. 2000, and references therein). Equating the mass-to-light ratio in clusters to the global value provides an estimate of the mass density of the universe; this estimate is subject to significant systematic error introduced by differences in galaxy populations between cluster cores and lower density regions (Carlberg et al. 1997; Girardi et al. 2000). Numerical simulations suggest that antibias in cluster cores may cause cluster mass-to-light ratios to exceed the universal value (Kravtsov & Klypin 1999; Bahcall et al. 2000; Benson et al. 2000). However, there are few measurements of mass-to-light ratios on scales of $1-10$ h^{-1}Mpc (Eisenstein et al. 1997; Small et al. 1998; Kaiser et al. 2001; Rines et al. 2000, hereafter R00) to test this conjecture.

Because clusters are not in equilibrium outside the virial radius, neither X-ray observations nor Jeans analysis provide secure mass determinations at these large radii. There are now two methods of approaching this problem: weak gravitational lensing (Kaiser et al. 2001) and kinematics of the infall region (Diaferio & Geller 1997; Diaferio 1999). Kaiser et al. analyzed the weak lensing signal from a supercluster at $z \approx 0.4$; the mass-to-light ratio (M/L_B=280 $\pm$40 for early-type galaxy light) is constant on scales up to 6 h^{-1}Mpc. Geller et al. (1999, hereafter GDK), applied the kinematic method of Diaferio & Geller (1997) to the infall region of the Coma cluster. GDK reproduced the X-ray derived mass profile and extended direct determinations of the mass profile to a radius of 10 h^{-1}Mpc. This method has also been applied to the Shapley Supercluster (Reisenegger et al. 2000), A576 (R00), the Fornax cluster (Drinkwater et al. 2001), and A1644 (Tustin et al. 2001). R00 found an enclosed mass-to-light ratio of $M/L_R \sim 300h$ within 4 h^{-1}Mpc.

Here, we calculate the infrared mass-to-light profile to a radius of 10 h^{-1}Mpc for the Coma cluster using photometry from the Two Micron All Sky Survey (2MASS, Skrutskie et al. 1997). Within a radius of 8.°0, the redshift survey is complete to $K_s = 12.2$ (622 galaxies), 1.2 magnitudes fainter than $M^*_{K_s}$ at the distance of Coma (Kochanek et al. 2001, hereafter K01). Infrared light is a better tracer of stellar mass than optical light, at least in late-type galaxies (Gavazzi et al. 1996); it is relatively insensitive to dust extinction and recent star formation. Despite these advantages, there are very few measurements of infrared mass-to-light ratios in clusters (Tustin et al. 2001). The physical scale at the redshift of Coma ($cz_\odot$ = 7093 km s^{-1}; cz_{CMB} = 7361 km s^{-1}) is 1° = 1.25 h^{-1}Mpc

($H_0 = 100\ h$ km s$^{-1}, \Omega_m = 0.3, \Omega_\Lambda = 0.7$; we assume Coma is at rest with respect to the CMB and use cz_{CMB} for all calculations).

2. Observations

2.1. Spectroscopy

We have collected 1779 redshifts (964 new or in press) within 8.°0 of the center of the Coma cluster (collected from ZCAT[5], NED[6], van Haarlem et al. 1993; Colless & Dunn 1996; Falco et al. 1999; Castander et al. 2001; Wegner et al. 2001, Geller et al. in preparation). We measured new redshifts with FAST, a long-slit spectrograph (Fabricant et al. 1998) on the 1.5-m Tillinghast telescope of the Fred Lawrence Whipple Observatory (FLWO). We selected targets from digitized images of the POSS I 103aE (red) plates. The redshift catalog is complete to $E \approx 15.4$ (845 galaxies). We later obtained a small number of redshifts ($\sim$20) to complete the $K_s \leq 12.2$ sample. Rines et al. (in preparation) describes this catalog in detail[7].

2.2. 2MASS Photometry

2MASS is an all-sky survey with uniform, complete photometry (Nikolaev et al. 2000) in three infrared bands (J, H, and K_s, a modified version of the K filter truncated at longer wavelengths). We use a preliminary version of the complete extended source catalog (Jarrett et al. 2000). Future recalibrations may change the zero-points of individual scans by up to 0.03 mag. We use the default K_s-band survey magnitudes which include light within the circular isophote corresponding to μ_{K_s}=20 mag/arcsec^2 (Jarrett et al. 2000). These magnitudes omit $\sim$15% of the flux (K01). The sky coverage of the catalog is complete to K_s=12.2. We include 2 galaxies not in 2MASS with K magnitudes from Gavazzi & Boselli (1996). There are 622 galaxies with $K_s \leq 12.2$ within 8.°0 of the center of Coma; all of these galaxies have measured redshifts. We make no correction for galactic extinction, which is negligible in the near-infrared at the North Galactic Pole.

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[5]Available at http://cfa-www.harvard.edu/~huchra/zcat

[6]Available at http://nedwww.ipac.caltech.edu

[7]The redshift catalog is available at http://tdc-www.harvard.edu/comacz/

3. Defining the Infall Region with Caustics

Figure 1 displays the projected radii and redshifts of galaxies surrounding Coma. The expected caustic pattern is easily visible; we calculate the shape with the technique described in Diaferio (1999) using smoothing parameter q of 10, 25, and 50 to test the variation caused by the subjective choice of this parameter. GDK show that the mass profile is robust with respect to limiting magnitude and non-uniform sampling. We recalculate the caustics based on additional redshifts collected since the calculation by GDK and find the same results. The cluster center is $\alpha = 13^h00^m00\overset{s}{.}7, \delta = 27°56'51''$ (J2000) and $cz_\odot = 7093$ km s^{-1} ($cz_{CMB} = 7361$ km s^{-1}). The center is 2.′3 SW of NGC 4884 and 5.′6 ESE of NGC 4874. The mass profile agrees with the NFW (Navarro et al. 1997) or Hernquist (1990) form but excludes a singular isothermal sphere. For the NFW profile, $r_s \simeq 0.17\ h^{-1}$Mpc and $r_{200} \simeq 1.5\ h^{-1}$Mpc ($r_{200}$ is the radius of the sphere with average mass density 200 times the critical density). Varying q changes the mass in the range 6-10 h^{-1}Mpc; the best-fit analytic form is NFW for q=10 and 25 but Hernquist for q=50. Unless otherwise stated, we use q=25 in later analysis (this choice yields the largest mass in the range 6-10 h^{-1}Mpc). GDK show that the mass profile agrees with independent X-ray mass estimates (Hughes 1989).

4. Mass-to-Light Profile

We subtract background and foreground galaxies (those outside the caustics) from the sample. K01 and Cole et al. (2001) use 2MASS to calculate the infrared field galaxy luminosity function (LF) and obtain nearly identical results. We adopt the values $M^*_{K_s} = -23.39 \pm 0.05$ and $\alpha = -1.09 \pm 0.06$ (K01) for 2MASS isophotal magnitudes. Measurements of the LF of the Coma cluster yield similar values of $M^*_{K_s}$ (Mobasher & Trentham 1998; de Propris et al. 1998; Andreon & Pelló 2000) and possibly a steeper faint-end slope ($\alpha \simeq -1.4 \pm 0.3$,$-0.8 \pm 0.4$ and -1.3 ± 0.3 respectively). At the distance of Coma, our sample extends 1.2 magnitudes fainter than $M^*_{K_s}$ and includes $\approx$ 68% of the total galaxy light. This fraction decreases to 56% if we adopt $\alpha = -1.3$. We assume the luminosity in faint galaxies traces that of the brighter galaxies. We estimate the light profile by summing up the luminosity in the bright member galaxies and multiplying by 1.47 to account for the luminosity contained in galaxies fainter than $K_s = 12.2$.

The resulting K_s band enclosed mass-to-light ratio is constant within 10 h^{-1}Mpc (Figure 2), where $M/L_{K_s} = 75 \pm 23h$. We estimate that the light profile is uncertain by $\approx$10% due to zero points, isophotal magnitudes, and the LF correction for faint galaxies. Systematic uncertainties in the determination of the LF could contribute additional uncertainty (e.g., Cole et al. 2001; Wright 2001). X-ray mass estimates (Hughes 1989) yield similar mass-

to-light ratios (67±32h within 2.5 h^{-1}Mpc) and show no radial trends. Table 1 lists the mass-to-light ratios inside and outside 1.6 h^{-1}Mpc $\approx r_{200}$ for all choices of q.

The light profile is projected; the mass profile is a radial profile. Figure 2 shows the best-fit projected Hernquist mass profile divided by the projected light profile. Although an NFW profile yields a better fit to the mass profile (for q=10, 25), the Hernquist profile is more centrally concentrated and thus shows an upper bound on this effect (assuming spherical symmetry). This profile shows that the mass-to-light ratio may decrease with radius. The mass-to-light ratio inside r_{200} is at most a factor of ~ 2.5 larger than that outside r_{200} (e.g., 87/36 for q=10 in Table 1).

5. Discussion

The K-band mass-to-light ratio of the Coma cluster within 10 h^{-1}Mpc is $75 \pm 23h$ as estimated from the light contained in galaxies brighter than $K_s = 12.2$ and the LF of K01. We make no correction for the ∼15% flux omitted by isophotal magnitudes. A steeper faint-end slope of $\alpha = -1.3$ would reduce the ratio to $62 \pm 19h$. Assuming a typical galaxy color of $B - K \sim 3.7$ (Jarrett 2000) and $(B - K)_\odot = 2.11$, we obtain $M/L_B \approx 329 \pm 103h$, in agreement with $M/L_B = 280 \pm 40h$ from weak lensing on a similar scale (Kaiser et al. 2001). At a radius of 3°, $M/L_B \approx 316 \pm 57h$; in agreement with Kent & Gunn (1982), who find $M/L_B \sim 362h$ at this radius. X-ray mass estimates yield estimates of $280 - 380h$ for a mass-follows-light model (Hughes 1989). We use a typical galaxy color of $R - K \sim 2.2$ and $(R-K)_\odot = 0.94$ to estimate $M/L_R \approx 243 \pm 72h$, in agreement with caustic estimates at large radii in A576 (R00). We estimate $M/L_H \approx 91 \pm 27h$, in agreement with $M/L_H = 82 - 127h$ in A1644 (Tustin et al. 2001).

The shape of the enclosed mass-to-light profile differs from the one measured in R band for A576. Instead of decreasing by a factor of two between the core and a radius of 4 h^{-1}Mpc, the enclosed mass-to-light ratio is constant within 10 h^{-1}Mpc. We propose two explanations of this difference. First, it may be a result of projection effects (Diaferio 1999); the shape of the mass-to-light profile may be affected by departures from spherical symmetry (R00). Second, if the K-band enclosed mass-to-light profile is flat in A576 as in Coma, a decrease in $R - K$ with radius leads to a decreasing profile in R-band. We expect such a trend if the star formation rate increases with radius as observed in other systems (e.g. Balogh et al. 2000). Infrared light profiles should be insensitive to recent star formation and best represent the distribution of stellar mass within the infall region. CCD R (K) photometry for Coma (A576) would resolve this issue. The color gradient effect becomes more significant at bluer wavelengths; we expect more steeply decreasing mass-to-light ratios with decreasing

wavelength (see Diaferio 1999; Bahcall et al. 2000).

In calculating the mass-to-light profile for Coma, we assume that the LF is independent of radius; changes in the LF with radius would affect the mass-to-light profile of Coma. Balogh et al. (2001) find different LFs in field, group, and cluster environments. Our survey includes 67, 69, and 65% of the total light in their field, group, and cluster LFs respectively assuming a Schechter form. Thus, uncertainties due to changes in the LF with environment contribute $\lesssim 7\%$ uncertainty to the light profile. Our data provide no constraints on galaxies fainter than $M^*_{K_s}$-1.2.

6. Summary

We calculate the mass-to-light ratio as a function of radius in the near-infrared K_s band for the Coma cluster. This calculation is one of the first measurements of a cluster mass-to-light ratio in the infrared. The mass-to-light profile extends to 10 h^{-1}Mpc and represents one of the largest scale measurements of a cluster mass-to-light ratio at any wavelength. Within 10 h^{-1}Mpc, the enclosed mass-to-light ratio is of $M/L_K = 75 \pm 23h$. With appropriate color transformations, this value agrees with previous optical and X-ray estimates for Coma (Kent & Gunn 1982; Hughes 1989) and estimates at scales of 1-6h^{-1}Mpc from infall mass estimates (R00) and weak lensing (Kaiser et al. 2001) in other systems.

The enclosed mass-to-light ratio is constant on scales up to 10 h^{-1}Mpc. This result implies that K-band light measured in bright galaxies traces the underlying mass distribution in clusters on scales of up to 10 h^{-1}Mpc. Uncertainties in the mass profile imply that the mass-to-light ratio inside r_{200} may be as much as a factor of ~ 2.5 larger than the ratio outside r_{200}, possibly due to antibias. K-band light is not positively biased with respect to mass; we cannot rule out antibias. Radial gradients in the star formation rate should create stronger observed antibias at shorter wavelengths (Kravtsov & Klypin 1999; Bahcall et al. 2000; Benson et al. 2000, R00).

The asymptotic value of $M/L_{K_s} = 75 \pm 23h$ implies $\Omega_m = 0.17 \pm 0.05$ using the K01 field galaxy luminosity function. Because we calculate magnitudes in the same manner as K01 from similar data, many potential systematic effects should affect our sample and the field galaxy luminosity function equally. A recent study of variations in the luminosity function with environment (Balogh et al. 2001) suggests that environmental effects contribute $\lesssim 7\%$ uncertainty to the light profile. Estimates of possible variations in M/L_{K_s} with radius (Table 1) suggest that the density parameter is no smaller than $\Omega_m \approx 0.08$. Similar studies of more distant clusters can produce better constraints if combined with weak lensing estimates.

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Table 1: RADIAL VARIATIONS IN M/L_{K_s}

q	M_{200} $10^{14}h^{-1}M_\odot$	$M(>r_{200})$ $10^{14}h^{-1}M_\odot$	$(M/L_K)_{200}$ $hM_\odot/L_\odot$	$(M/L_K)(>r_{200})$ $hM_\odot/L_\odot$	$(M/L_K)(<10\ h^{-1}\mathrm{Mp}$ $hM_\odot/L_\odot$
10	8.0±0.6	7.7±1.3	71±9	60±12	65±14
10 H[a]	9.7	4.7	87	36	60
25	8.1±0.8	10.2±2.8	72±10	79±23	75±23
25 H[a]	10.1	5.6	91	43	65
50	8.5±1.8	6.7±3.3	76±18	51±26	63±35
50 H[a]	10.1	5.5	91	42	64

[a]projected best-fit Hernquist profile

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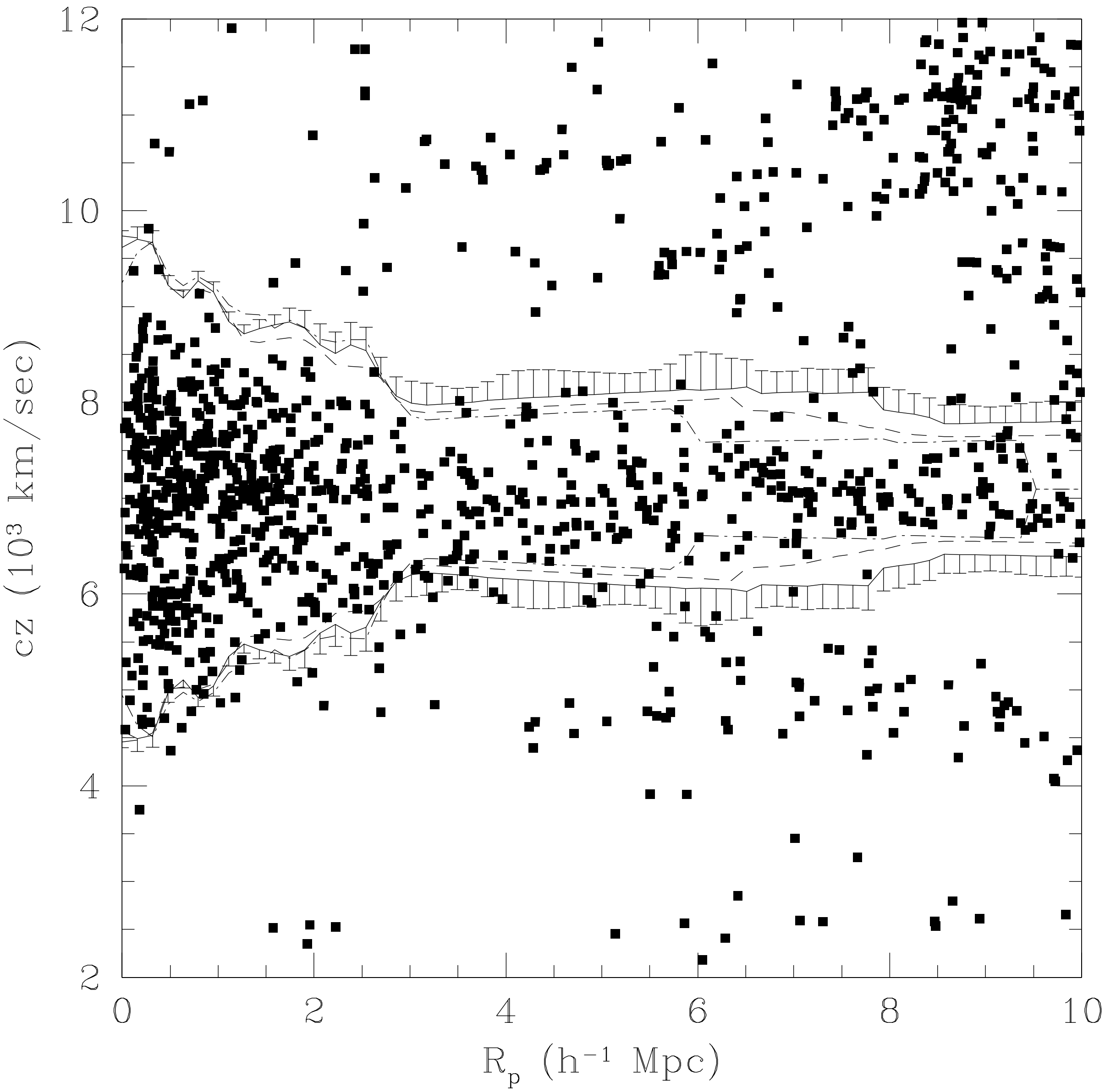

Fig. 1.— Redshift versus projected radius of galaxies around the Coma cluster. The trumpet-shaped caustic pattern which defines the infall region is clearly visible. The dashed, solid, and dashed-dotted lines show the location of the caustics for $q = 10$, 25, and 50 with $1-\sigma$ uncertainties shown for $q = 25$. For clarity, the uncertainties are only displayed away from the cluster.

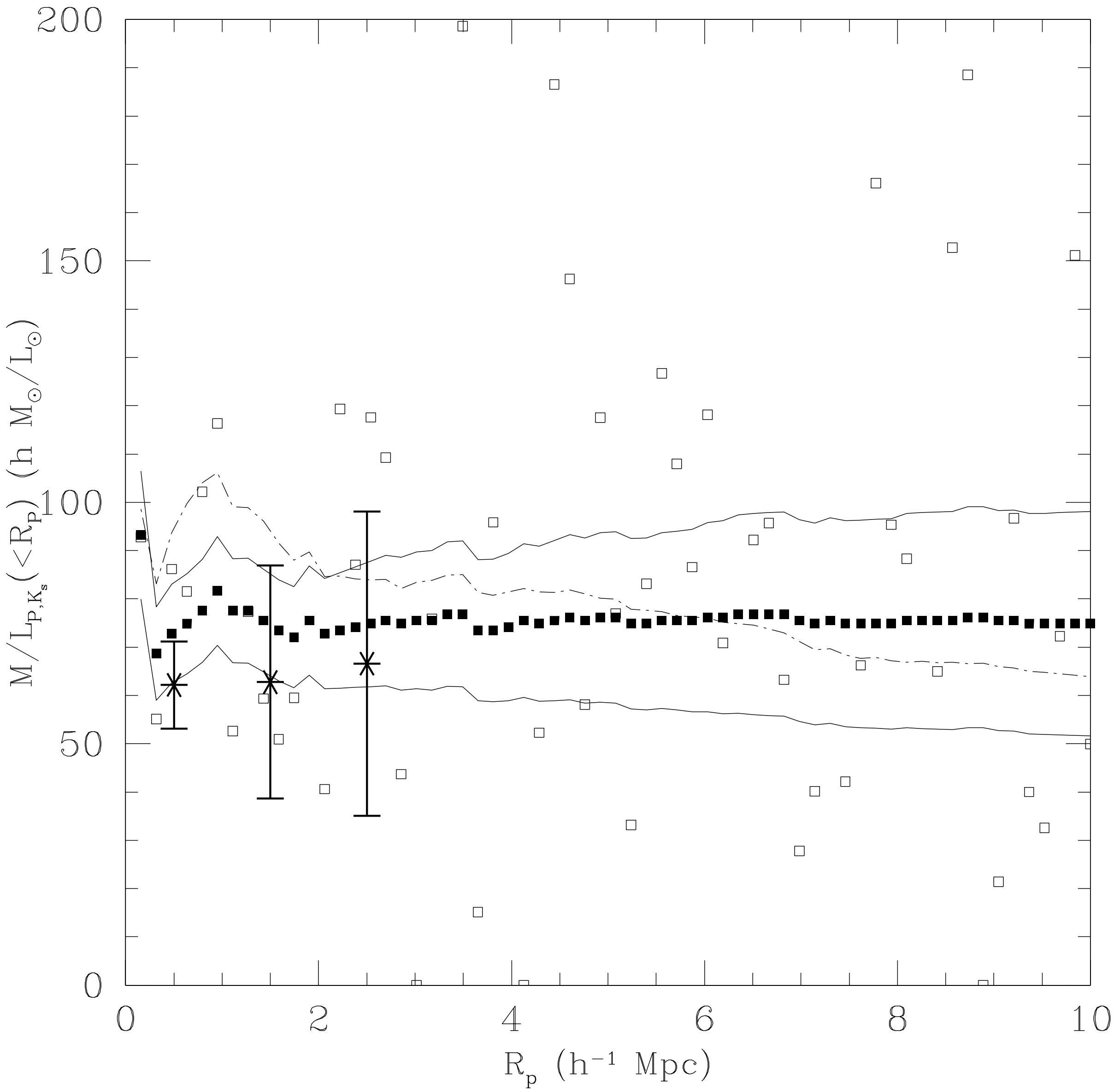

Fig. 2.— Filled squares indicate the enclosed mass-to-light ratio as a function of radius; the solid lines show $1-\sigma$ uncertainties. Open squares show the mass-to-light ratio in each spherical shell. The dash-dot line indicates the best-fit projected Hernquist mass profile divided by the (projected) light profile. Stars show the mass-to-light profile from X-ray mass estimates (Hughes 1989).